Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 61 (2015) 55 – 60
Physics Procedia

13th International Conference on Topics in Astroparticle and Undergound Physics, TAUP2013

Searching for Sub-Gev Dark Matter at Fixed Target Neutrino Experiments

Patrick deNiverville

Department of Physics and Astronomy, University of Victoria
Victoria, BC, V8W 2Y2 Canada

Abstract

Low mass dark matter theories, if produced as a thermal relic in the early universe, must be accompanied by light mediators in order to obtain the dark matter abundance observed in the present day universe. These light mediators in turn provide a channel for the production of dark matter at fixed target neutrino experiments, producing a relativistic dark matter beam, which could then be detected by neutral-current-like interactions in neutrino detectors. We consider the possibility that fixed target neutrino experiments such as MiniBooNE and T2K could serve as a new dark matter search avenue, sensitive to sub-GeV dark matter scenarios that would be otherwise undetectable. These experiments are found to provide sensitivity to light stable states that could serve as viable candidates for particle dark matter.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords:
dark matter, neutrino beam, thermal relic, hidden sector

1. Introduction

Thermal relic dark matter possessing a mass below a few GeV is overproduced in the early universe unless some additional light states are introduced to mediate their interactions with the Standard Model. These hidden sector scenarios are perhaps the only means of introducing a viable sub-GeV thermal relic dark matter candidate. Constraining the parameter space of these scenarios is difficult, as by construction they escape many cosmological constraints, and they leave little in the way of signals detectable by direct and indirect dark matter searches. New strategies, using high-intensity experiments utilizing GeV electron and proton beams to study rare or weakly coupled states show great promise in allowing further exploration of this parameter space. We show the effectiveness of searches by Fixed Target Neutrino Experiments by studying a hidden $U(1)'$ scenario, mediated by a vector boson that kinetically mixes with the photon. As much of this work has been discussed in previous publications, we direct the reader to [1, 2] for details on the development of and reasoning behind the scenario, and to [3, 4] for more details on how the sensitivity of each experiment was calculated. This work will primarily be devoted to new developments since those papers, with a description of the existing constraints on the scenario in section 2 and some example sensitivity curves for two fixed target experiments, T2K and MiniBooNE, in section 3.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory
doi:10.1016/j.phpro.2014.12.010

2. Scenario

We consider a hidden sector scenario charged under a U(1)′ symmetry, spontaneously broken by some Higgs′ at a low energy scale and mediated by a vector boson V,

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F_{\mu\nu} + |(\partial_\mu - e' V_\mu)\chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'}, \tag{1}$$

where $V_{\mu\nu}$ and $F^{\mu\nu}$ are the U(1)′ and electromagnetic field strengths, and κ is the kinetic mixing strength between the V and the photon. Note that while the V does mix with the Z boson, we will not consider the effect of this mixing as these interactions would be suppressed by the Z mass.

The scenario possesses four free parameters: κ, the coupling strength of the U(1)′ symmetry $\alpha' = e'^2/(4\pi)$, and the masses m_V and m_χ. We are primarily interested in dark matter masses m_χ between a few MeV and 1 GeV, as this region is not yet constrained by direct dark matter searches. We also require $m_V \geq 2m_\chi$ so that the invisible decay $V \to \chi\bar{\chi}$ is kinematically allowed, and dominates over the visible decays to Standard Model particles for sufficiently small values of κ. Finally, we have chosen to set α' equal to 0.1. Larger values are of course possible so long as the dark matter does not self-interact too strongly and the theory remains perturbative.

This scenario escapes many cosmological constraints due to the velocity suppression of the p-wave annihilation cross section, and is not yet subject to the increasingly sensitive limits placed by direct searches due to the low mass of the dark matter candidate. It is subject to limits placed by a number of experimental measurements relating to rare decays, missing energy searches and precision Standard Model measurements. In order to display the scenario parameter space and the regions already excluded, we show two 2-dimensional slices of the parameter space in figure 1. The left-hand plot is similar in many ways to the dark force or hidden/heavy photon constraint plots (see i.e [5]), and presents the parameter space in terms of κ and m_V for a constant m_χ and α'. The right-hand plot is on the same axes as the direct detection sensitivity plots used by many experiments, and includes the best direct detection limits from a number of experiments. The direct detection plot is effectively in terms of κ^2 and m_χ for a fixed m_V and α'.

Visible decays of the V provide some weak limits on the scenario parameter space, as V's can be produced at even low energy experiments, and have very short lifetimes. While these searches provide a significant constraint on heavy photons, visible decays suppressed by a factor of $\alpha\kappa^2/\alpha'$ in the hidden sector scenario, as the V preferentially decays to invisible, hidden sector states. These limits are labeled e^+e^- in figure 1.

Of greater concern is the V's contribution to invisible decay widths and missing energy searches. Decays of the π^0 to a single photon and missing energy, and contributions to the invisible width of the J/ψ are both included on the plot, with the later providing the best constraints on some portions of the low mass parameter space. Searches for $pp \to$ jet + invisble must also be considered, though current analyses do not rule out much of the parameter space. Far greater constraints come from monophoton searches by BaBar, which provide the best limits over much of the parameter space.

The hidden sector scenario makes extra contributions to many precision measurements of SM quantities through the introduction of additional diagrams involving the V. Shifts in the electron magnetic moment g-2 place some of the best constraints on the parameter space at the very low end of the m_V range. Shifts in the muon magnetic moment are more complicated, as there is already great disagreement between theory and experiment. We have chosen to exclude parameter space that increases the disagreement between the theoretical prediction and experimental measurements to more than 5σ. The V could ameliorate the disagreement between theory and experiment, and the light blue band through the parameter space indicates the region of the parameter space where a better than 3σ agreement exists between theory and experiment. Virtual V exchanges can also have a measurable effect on the Z^0 mass, and this has been labeled as "Δm_Z and EW fit" in the constraint plots.

3. Sensitivity at Fixed Target Neutrino Experiments

Fixed Target Neutrino Experiments (FTNEs) provide an alternative probe of the hidden-sector parameter space. These experiments are capable of producing large numbers of relativistic hidden sector states

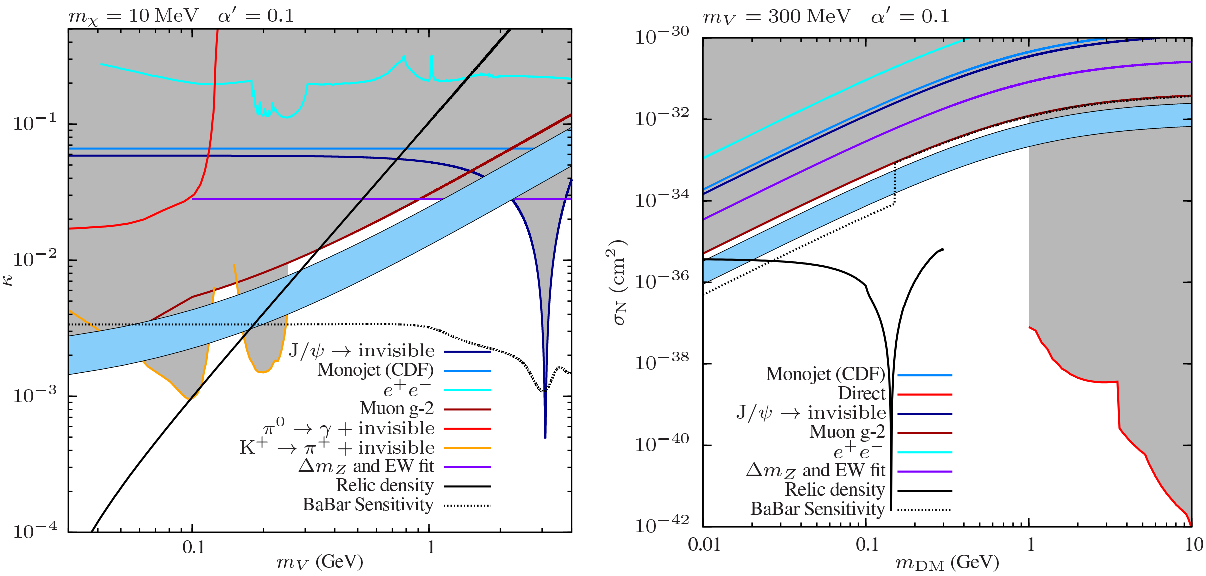

Fig. 1. The dark force parameter space for the hidden sector scenario is shown in a κ vs m_V plot on the left, while the direct detection parameter space is shown in terms of the dark matter-nucleon scattering σ_N and m_χ on the right. The shaded region is excluded by existing constraints. The constraints shown are from limits on $\pi^0 \to \gamma$ + invisible [6], $J/Psi \to$ invisible [7] and $pp \to$ jet + invisible (labeled monojet) [8], dark force searches by MAMI, BaBar, APEX and KLOE (labeled as e^+e^-) [5], excessive contributions to electron and muon g-2 [9, 10, 11, 12, 13], a monophoton search by BaBar (labeled BaBar sensitivity) [14, 15, 16] and deviations in precision SM measurements[17]. The right-hand plot also features the best limits published by XENON10 [18], DAMIC [19], CDMSlite [20], XENON100 [21], and LUX [22] as of March 2014. The black line through the parameter space (labeled Relic density) traces the combination of parameters that reproduce the observed matter density of the universe. The light blue band through the parameter space marks where the scenario brings theory and experiment into better than 3σ agreement. Note that the parameter space above the BaBar line is indeed excluded, though currently not greyed in so as to show regions of the parameter space of interest. Further details are provided in the text.

through either the radiative decays of neutral mesons or direct production through parton-level interactions. V production through π^0 and η decays provides sensitivity to portions of the parameter space with $m_V \le m_\eta$, while direct production can probe $m_V \ge 1$ GeV. This leaves a gap in the coverage of the scenario parameter space that will be examined in future work. The produced V's decay into $\chi\bar{\chi}$ pairs before exiting the target, resulting in the creation of a "dark matter beam" alongside the observed neutrino beam. These hidden-sector dark matter candidates propagate through the neutrino detector where they could then be detected as excess neutral-current-like scattering events above those produced by scatterings of the neutrino beams. With their large data sets and low Standard Model backgrounds, FTNEs can achieve impressive sensitivity through a relatively straightforward counting experiment.

For V masses below the mass of the π^0, the most significant constraints on this scenario are placed by the observation of 55 nonstandard NCE scattering events at a 90% confidence level at the LSND experiment [23]. The sensitivity of the experiment was studied in previous works [2, 3], and we recast those results here by excluding all of the parameter space for which LSND would expect to observe more than 110 dark matter scattering events, where we have chosen a weaker constraint to allow for up to a factor of two error in the π^0 production estimates. This curve is included as a constraint line in the sensitivity plots which follow. The beam energy at LSND is too low to produce any neutral mesons apart from the π^0 in large quantities, and so the experiment is incapable of probing larger V masses.

A disadvantage of probing the hidden sector parameter space through counting experiments is that a substantial Standard Model background remains in the form of neutrinos. A possible strategy for the reduc-

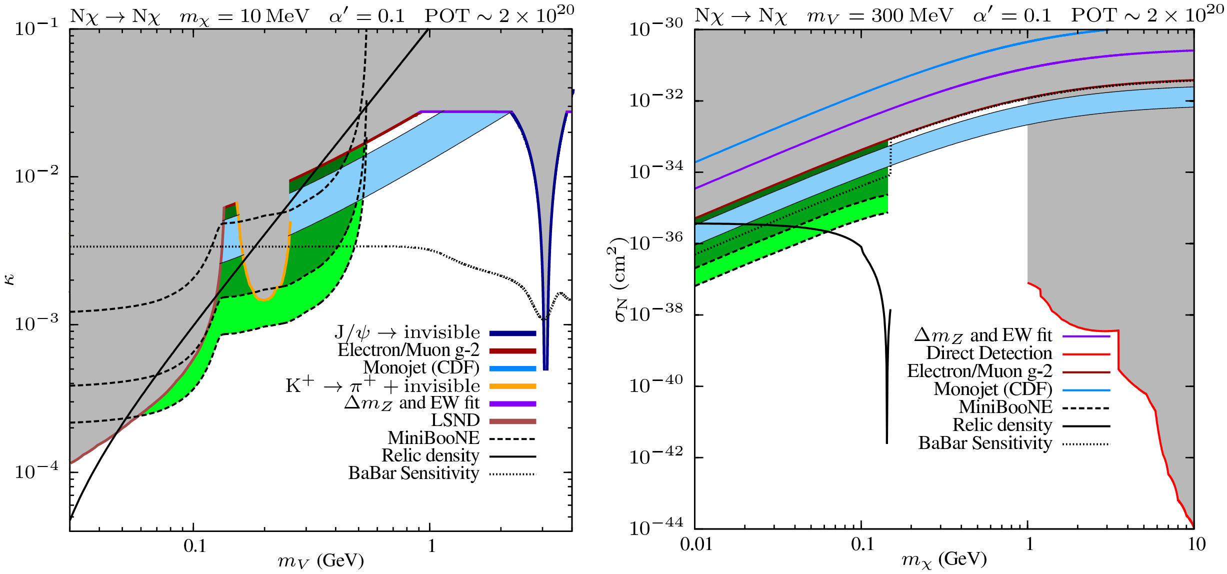

Fig. 2. Plots of the projected sensitivity of the MiniBooNE experiment to the hidden sector scenario over the dark force and direct detection parameter spaces with the Protons on Target of the proposed beam dump run. The shaded green regions correspond to 1-10 events (light), 10-1000 events (medium) and more than 1000 events (dark).

tion of this background is to perform an off-target or beam dump experiment. By colliding the proton beam with the beam stop rather than the target, the charged mesons responsible for the production of the majority of the neutrino beam are reabsorbed before they can decay, substantially reducing the number of neutrinos produced. Backgrounds can be further reduced using timing information, and differences in the expected energy and angular distribution of the neutrino and dark matter beams. One such effort is currently under way using the MiniBooNE detector at Fermilab, where the proton beam is being directed around the target into a beam dump 50 m away. The 8.9 GeV MiniBooNE beam is of higher energy than that of LSND, and provides sensitivity to $m_V \leq m_\eta$. More details on the beam dump run can be found in the proposal to the Fermilab PAC [24][1]. We show sensitivity estimates for the run proposal number of Protons on Target (POT) of 2×10^{20} in figure 2. Note that the beam dump run is capable of covering much of the g-2 favoured band, a region of the parameter space which is of particular interest.

The T2K experiment, with its larger beam energy of 30 GeV provides sensitivity to a much larger mass range than LSND or MiniBooNE, with access to all of the production channels mentioned above. The T2K experiment is an off-axis long-baseline neutrino experiment, and uses the 295 km distant Super-K detector to study neutrino oscillations. The original neutrino beam is studied using a multi-component off-axis near detector called ND280, located 280 m from the production target. We show the estimated sensitivity of a counting experiment using a component of ND280 called the P0D to the hidden-sector scenario in figure 3. It is difficult to determine the true sensitivity of the P0D to the hidden-sector scenario, as we do not yet know how large a neutrino background is to be expected, though it is unlikely to be able to compete with the limits set by BaBar.

[1]The beam dump run was officially approved by the Fermilab PAC in January 2014.

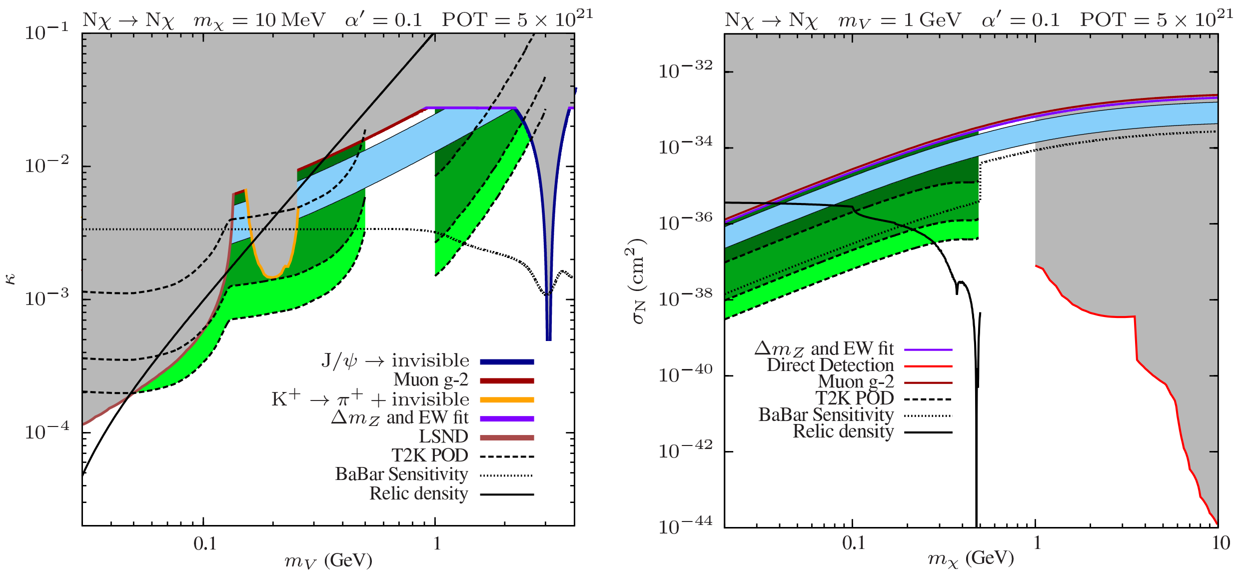

Fig. 3. Plots of the projected sensitivity of T2K's P0D detector to the hidden sector scenario over the dark force and direct detection parameter spaces over the lifetime of the T2K experiment. The green shaded regions correspond to 1-10 events (light), 10-1000 events (medium) and more than 1000 events (dark).

4. Conclusion

Fixed target neutrino experiments provide large data sets with low Standard Model backgrounds, which allow for the undertaking of very sensitive searches for weakly-coupled sub- to few GeV new physics states. We examined a hidden-sector scenario that provides a viable sub-GeV thermal relic dark matter candidate with a parameter space that is largely unconstrained by standard dark matter search techniques and only weakly constrained by a number of particle physics searches for hidden photons. At low masses, fixed target neutrino experiments clearly provide the best limits on this parameter space with a straightforward counting experiment. Experiments with smaller data sets, but larger energies, are capable of providing significant limits on the parameter space by discriminating between hidden-sector and neutrino events using differences in the timing, angular and energy distributions of the particle species, or with greater effort, by reducing the number of neutrinos produced altogether. While impressive new constraints are being placed on the hidden-sector dark matter parameter space by analyses of FTNEs and electron colliders such as BaBar, a great deal of viable and interesting parameter space remains, which can only be explored by new experiments.

Acknowledgement

The work of P. dN is supported in part by NSERC, Canada.

References

[1] M. Pospelov, A. Ritz, M. B. Voloshin, Secluded WIMP Dark Matter, Phys.Lett. B662 (2008) 53–61. `arXiv:0711.4866`, `doi:10.1016/j.physletb.2008.02.052`.

[2] B. Batell, M. Pospelov, A. Ritz, Exploring Portals to a Hidden Sector Through Fixed Targets, Phys. Rev. D 80 (2009) 095024. `arXiv:0906.5614`, `doi:10.1103/PhysRevD.80.095024`.

[3] P. deNiverville, M. Pospelov, A. Ritz, Observing a light dark matter beam with neutrino experiments, Phys. Rev. D 84 (2011) 075020. arXiv:1107.4580.

[4] P. deNiverville, D. McKeen, A. Ritz, Signatures of sub-GeV dark matter beams at neutrino experiments, Phys.Rev. D86 (2012) 035022. arXiv:1205.3499, doi:10.1103/PhysRevD.86.035022.

[5] J. Hewett, H. Weerts, R. Brock, J. Butler, B. Casey, et al., Fundamental Physics at the Intensity FrontierarXiv:1205.2671.

[6] M. Atiya, I. Chiang, J. Frank, J. Haggerty, M. Ito, et al., Search for the decay pi0 to gamma X, Phys.Rev.Lett. 69 (1992) 733–736. doi:10.1103/PhysRevLett.69.733.

[7] M. Ablikim, et al., Search for the invisible decay of J / psi in psi(2S) — pi+ pi- J / psi, Phys.Rev.Lett. 100 (2008) 192001. arXiv:0710.0039, doi:10.1103/PhysRevLett.100.192001.

[8] I. M. Shoemaker, L. Vecchi, Unitarity and Monojet Bounds on Models for DAMA, CoGeNT, and CRESST-II, Phys.Rev. D86 (2012) 015023. arXiv:1112.5457, doi:10.1103/PhysRevD.86.015023.

[9] M. Pospelov, Secluded U(1) below the weak scale, Phys.Rev. D80 (2009) 095002. arXiv:0811.1030, doi:10.1103/PhysRevD.80.095002.

[10] R. Bouchendira, P. Clade, S. Guellati-Khelifa, F. Nez, F. Biraben, New determination of the fine structure constant and test of the quantum electrodynamics, Phys.Rev.Lett. 106 (2011) 080801. arXiv:1012.3627, doi:10.1103/PhysRevLett.106.080801.

[11] D. Hanneke, S. F. Hoogerheide, G. Gabrielse, Cavity Control of a Single-Electron Quantum Cyclotron: Measuring the Electron Magnetic MomentarXiv:1009.4831.

[12] T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, Tenth-Order QED Contribution to the Electron g-2 and an Improved Value of the Fine Structure Constant, Phys.Rev.Lett. 109 (2012) 111807. arXiv:1205.5368, doi:10.1103/PhysRevLett.109.111807.

[13] M. Endo, K. Hamaguchi, G. Mishima, Constraints on Hidden Photon Models from Electron g-2 and Hydrogen Spectroscopy, Phys.Rev. D86 (2012) 095029. arXiv:1209.2558, doi:10.1103/PhysRevD.86.095029.

[14] B. Aubert, et al., Search for Invisible Decays of a Light Scalar in Radiative Transitions $\upsilon_{3S} \rightarrow \gamma$ A0arXiv:0808.0017.

[15] E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, New Electron Beam-Dump Experiments to Search for MeV to few-GeV Dark MatterarXiv:1307.6554.

[16] R. Essig, J. Mardon, M. Papucci, T. Volansky, Y.-M. Zhong, Constraining Light Dark Matter with Low-Energy e+e- CollidersarXiv:1309.5084.

[17] A. Hook, E. Izaguirre, J. G. Wacker, Model Independent Bounds on Kinetic Mixing, Adv.High Energy Phys. 2011 (2011) 859762. arXiv:1006.0973, doi:10.1155/2011/859762.

[18] J. Angle, et al., A search for light dark matter in XENON10 data, Phys.Rev.Lett. 107 (2011) 051301. arXiv:1104.3088, doi:10.1103/PhysRevLett.107.051301.

[19] J. Barreto, et al., Direct Search for Low Mass Dark Matter Particles with CCDs, Phys.Lett. B711 (2012) 264–269. arXiv:1105.5191, doi:10.1016/j.physletb.2012.04.006.

[20] R. Agnese, A. Anderson, M. Asai, D. Balakishiyeva, R. B. Thakur, et al., CDMSlite: A Search for Low-Mass WIMPs using Voltage-Assisted Calorimetric Ionization Detection in the SuperCDMS ExperimentarXiv:1309.3259.

[21] E. Aprile, et al., Dark Matter Results from 225 Live Days of XENON100 Data, Phys.Rev.Lett. 109 (2012) 181301. arXiv:1207.5988, doi:10.1103/PhysRevLett.109.181301.

[22] M. Szydagis, et al., A Detailed Look at the First Results from the Large Underground Xenon (LUX) Dark Matter ExperimentarXiv:1402.3731.

[23] L. Auerbach, et al., Measurement of electron - neutrino - electron elastic scattering, Phys.Rev. D63 (2001) 112001. arXiv:hep-ex/0101039, doi:10.1103/PhysRevD.63.112001.

[24] R. Dharmapalan, et al., Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE RunningarXiv:1211.2258.